Road network circuity in metropolitan areas

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Abstract

Circuity, the ratio of network to Euclidean distances, describes the directness of trips and the efficiency of transportation networks. This paper measures the circuity of the 51 most populated Metropolitan Statistical Areas (MSAs) in the United States and identifies trends in those circuities between 1990 and 2010. Overall circuity has increased between 1990 and 2010: random points have not only become farther apart in distance, their shortest network path has become more circuitous, suggesting that the more recently constructed parts of street networks are laid out more circuitously than older parts of the network. Over this period, 35 MSAs experienced a statistically significant increase in circuity (6 experienced a significant decrease). As expected, short trips are more circuitous than long trips. A new circuity distance decay function describes how circuity varies with distance within metropolitan areas. The parameters of this function have changed from 1990 to 2010.

Keywords: Circuity, directness, network structure, cities.

Introduction

Circuity, the ratio of network to Euclidean distance along a path, is an important metric in the emerging field of network structure [2, 3, 7, 8, 15, 17, 22, 23, 26, 28]. Interest in the implications of network circuity are long held. Circuity has been used to aid in the placement of centralized facilities [9, 10], selecting highway alignments [13], and organization of shipping logistics [24, 27, 31]. Average circuity has previously been estimated at about 1.2 times the Euclidean distance for stylized road networks [21], but is known to vary by country due to factors such as network density [1].

Circuity may be reduced simply by increasing connectivity on a network, by providing a higher number of links into the junctions (intersections) that currently exist. With any investment comes a trade-off between construction, operations, and maintenance costs and increased utility from the network [6, 35]. Economies of scale and density associated with aggregating traffic on networks provide advantages to more circuitous routes that a simple

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distance measure does not capture. With every network there are associated traffic capacities which play into a decreased return on investment into a road network [5]. This problem of network design is perhaps the most analytically difficult problem within transportation [36], requiring a "whole-network" traffic analysis [14]. Further, topography constrains the ability to reduce circuity [11].

This study measures the circuity for road networks in the 51 most populous Metropolitan Statistical Areas (MSAs) in the United States for 1990, 2000, and 2010. If circuity changes, this implies that the design of networks has changed. If circuity increases, it implies networks are less efficient from a shortest distance path perspective (though may be as or more efficient from a shortest travel time path, as not all links have the same speeds). This study also examines how circuity varies with the length of Origin-Destination pairs (OD Pairs), estimating a measure of distance decay for circuity.

The subsequent sections present the results and compare cities and trends over time, and look at how circuity decreases with distance. Implications about changing urban form are identified in Section . Details of the methods and definitions are provided in Section .

Results

Circuity Measurement

Table 1 shows the unweighted circuities as calculated in Equation 1 for trips up to 60 km in 51 MSAs for 1990, 2000, and 2010. Student t-tests were performed between data from 1990 and 2010. Respective p-values and confidence intervals are tabulated in the last columns.

Unweighted circuity is calculated as :

$$C_u = \frac{\sum D_n}{\sum D_E} \tag{1}$$

where:

C_u = Average Unweighted Circuity,

D_n = Sum of the network distances between all origin-destination pairs in the subsample,

D_E = Sum of the Euclidean distances between all origin-destination pairs in the subsample.

Similarly, Table 2 shows the results of commute trip length frequency weighted circuities from Equation 2 (as described in Section). Calculated in the bottom row of Table 2 is the average (weighting all 51 cities equally) for each year analyzed (1990, 2000, 2010). In these averages, a clear increasing trend can be seen.

The weighted circuity of a road network, weighted by the distribution of home to work trips traveled in the MSA:

$$C_w = \frac{\sum_{i=1}^{I} T_i C_i}{\sum_{i=1}^{I} T_i} \tag{2}$$

where:

C_w = Weighted circuity of trips less than or equal to threshold S,

T_i = Number of trips in each interval,

C_i = Unweighted circuity of trips in the interval i (based on network distances), interval size $s = 5km$, threshold $S = 60km$, total number of intervals $I = S/s = 12$.

Table 3 summarizes the trends in circuity. For example, 1990-2000-2010 means that the weighted circuity was lowest in 1990, higher in 2000, and highest in 2010. As can be seen in Table 3, the first three possibilities listed have 1990 with a lower weighted circuity value than 2010. Of 51 metropolitan areas, 41 yielded statistically significant results, 35 metropolitan areas showed statistically significant increases, and 6 showed statistically significant decreases.

When comparing Tables 1 and 2 it is almost always the case that the unweighted circuity is lower than the weighted circuity for an MSA in any of the years analyzed. The only cases where the unweighted circuity is higher than the weighted circuity were Honolulu and Salt Lake City for all three analyzed years, the 1990 versions of San Diego and Las Vegas, and the 2000 road network of Las Vegas.

Circuity vs Trip Length

In Figure 1 trends for trips generated within the Minneapolis MSA are shown. C_i shows an unweighted circuity value according to Equation 1 over a certain network distance interval (i) for each decade. We can similarly draw this for network travel time intervals (C_t). Circuity decreases as the travel distance and time increases. These observations corroborate previous findings [17] that higher circuities are experienced with shorter commutes.

Circuity can be modeled exponentially [16]. In searching for the best exponential fit, when looking at unweighted circuity and travel time, linear fits were explored for all 51 MSAs in the study on linear plots, double-log plots, and both semi-log plots. The double-log plot gave the best fit (r^2) for all three years analyzed in the study (1990, 2000, and 2010). The corresponding equation follows:

$$C_t = e^{\beta} \cdot t^{\zeta} \tag{3}$$

where:

C_t = unweighted circuity for some timeband (t),

ζ = circuity decay parameter to be estimated, and

β = constant to be estimated.

Table 4 summarizes the results. As can be seen zeta decreases on average from -0.035 to -0.039 from 1990 to 2010, indicating that if the betas were constant, circuity would be lower in 2010 than 2000, which would be lower than 1990. However, β also varies slightly over time, so the estimated average circuity is lowest in 1990 for trips under 60 minutes, followed by 2010, with 2000 having the highest values, as shown in Figure 2.

Figure 3 shows the ability of Equation 3 to model circuity data. The plotted points in Figure 3 show US averages for circuity in each time interval. The plotted curve is a representation of the circuity using Equation 3. Error bars are plotted to show the distribution of data points from all 51 MSAs. As can be seen, there is high overlap of the circuities between cities, and the difference between cities is much greater than the difference between years.

Discussion

This paper quantifies road network circuity in MSAs across the United States. The results enable calculation of other measures, such as job accessibility [16]. The paper finds average weighted circuity increasing from 1.327 in 1990 to 1.339 in 2010. Given that 1.0 is the minimum possible circuity, this represents a 3.7% increase. Some areas such as Seattle, shaped by bodies of water, see values above 1.4. Over the period from 1990-2010, 35 of the United States' 51 most populated MSAs experienced statistically significant increases in circuity.

So in the most populated MSAs in the United States, random points have not only become farther apart in distance, they are becoming more circuitous, suggesting that the more recently constructed parts of street networks are laid out less efficiently than older parts of the network.

It is not surprising that new areas are less well connected than older areas, as that is part of the general process of network growth and infill [18]. But the trend must be that they stay less well connected, or that the amount of new network is becoming disproportionately significant.

Specific patterns of suburbanization [4, 12, 19, 20, 25, 29, 30] are thus suspects in this circuity increase, and it is posited that this continued trend of progression areas with a more dendritic and hierarchical road network causes the general increase in circuity over the past few decades. Exploring the connections between intra-metropolitan location and network structure and daily travel is an important line of future research. Determining causality, and whether influencing the circuity of an MSA could influence metropolitan economic productivity and agglomeration economies bears great potential for future research.

Methods

Data Collection and Generation

Metropolitan Statistical Areas (MSA) as defined in 2009 by the Census for 2010 were used as a basis for this study, ensuring a consistent geography for all three points in time. MSA boundaries change decennially. It was considered to use the definitions from 1990 and 2000 with the Census road network data from 1990 and 2000 respectively, but this was decided against for two reasons. First, the definitions change drastically with some MSAs. For instance, in 1990, the Phoenix MSA definition only included Maricopa County. By 2009, the MSA definition included Pinal County as well. Another issue considered the definition of Consolidated Metropolitan Statistical Areas (CMSA) as opposed to Metropolitan Statistical Areas. This can be contrasted with Census nomenclature used in 1990, where within MSAs there were Primary Metropolitan Statistical Areas (PMSA), different markedly from the definitions in 2009. A good example of this is Pittsburgh where in 1990 the area was divided into two PMSAs and in 2009 the counties were listed together in one MSA. In 2009, the Census did not define CMSAs nor PMSAs, and instead defined Metropolitan Divisions within MSAs.

Sampling

Sampling of origins and destinations occurred randomly across the network. Points could fall on any polygon representing a link. In calculations, the distance from the network link nearest the point was used. For areas with no roads, no points would be generated. Figure 4 depicts a portion of the Miami MSA with sample origins. As can be seen, points fall on the polygon containing the center-lines of roads, such as in rural areas, so the distribution of points is proportional to the location of roads. This alone does not account for the distances and circuities actually experienced between home and work locations, so we applied survey data from the NHTS to account for the actual distribution of trip distances. The circuity differences between ignoring actual trip distance distributions over the MSAs and accounting for them are evidenced in Tables 1 and 2 respectively.

The 2000 and 2010 MSA networks were projected onto state planar coordinates, North American Datum (NAD) 1983. Files for the 1990 road networks were created using NAD 1927, and a conversion to 1983 was required. Using GIS software (ArcGIS), 500 points generated over the MSA represented randomly located home origins, and 100 points generated represented work destinations. The product of the home and work points, about 50,000 origin-destination (OD) pairs, representing "trips", were generated for each MSA. Ideally, 50,000 origin-destination pairs, would be generated, though it was common that a few points would fail to have network paths connecting them, resulting in a total generation of trips slightly under 50,000 for each year for each MSA. The shortest distance path on the road network of the MSA was calculated for each OD pair. Euclidean distances were computed as well.

NHTS Data

The NHTS conducted surveys in 1990, 1995, 2001, and 2009 [32, 33, 34]. Data from 1995 (and subsequent years) was collected in a different manner than in 1990, Data from 1995 was used for 1990 trip length distribution because the way data was collected in 1990 made it incomparable to data from subsequent years. Those surveys are overlaid with the data generated from the road networks of 1990, 2000, and 2010 respectively. For some MSAs, data were not collected by the NHTS for all three surveys, and proxies (values from the nearest year for which data were collected) were used. MSAs that did not have survey data for the 1995 survey are: Atlanta, Grand Rapids, Honolulu, Jacksonville, Louisville, Providence, and Raleigh. For those MSAs, survey data from 2001 was used as weights. The only MSA that did not have survey data for just the 2009 survey was Honolulu, for which survey data from 2001 was used. Adjoining MSAs were combined in the NHTS in some years, specifically, Baltimore and Washington, DC were listed separately in 1995, but were combined for the 2001 and 2009 surveys.

Sample Size

Determining an appropriate sample size is essential to minimizing the computational time incurred when analyzing an OD Matrix in a road network. To do so, many simulations were run on the road network of Miami, Florida. Miami was chosen because it is a large MSA that has relatively few (three) counties (Broward, Miami-Dade, and Palm Beach), relatively simple to manage. Five simulations were run for each OD matrix of 2,000, 8,000, 50,000, and 200,000 trips respectively, 20 simulations in total. Unweighted circuity values were used as a measure, as this is the raw data. The results of these iterative tests can be seen in Table 5. Obviously from each set of generated OD pairs, the unweighted circuity value will differ slightly from test to test. After a few trials with each matrix the results of that matrix are reproducible.

The standard deviation (σ) of these results were used to determine what size matrix to use for testing the remaining MSAs. Since the standard deviation of unweighted circuity results as calculated in Equation 1 does not decrease beyond 50,000 trips generated, the sample size chosen for all MSAs was 50,000 trips. With a standard deviation (σ) of 0.0064, this creates a 95% confidence interval of ± 0.0126 in the unweighted circuity value. Each of the 51 MSAs has matrices generated for 1990, 2000, and 2010. That is 153 iterations, and with a 95% confidence interval; it is expected that approximately 7 or 8 of those iterations would fall outside the aforementioned confidence interval.

Weighted Circuity

All statistics in this paper are summarized by Metropolitan Statistical Area (MSA) as defined by US Bureau of the Census. Each MSA has its own profile identifying what percentage of workers travel certain distances to work, and the results of an unweighted circuity calculation will disproportionately measure the longer trips, both because longer distances carry more weight in Equation 1 and because more long trips exist in a random sampling of pairs of points than short trips. Weighted circuities are tabulated in Table 2.

To ensure the measures are reasonable, weighted circuity is computed, weighting the network origin-destination pairs by the likelihood of that distance appearing in actual home to work commutes. Survey data came from the National Household Travel Survey. Actual data were collected in units of miles. For this study these were converted to kilometers (NHTS) and employed to weight for home-work trip distances (e.g. more people choose a commute distance of 5-10 km than 55-60 km).

The geographic area for weighting needs to be considered because some MSAs are smaller than others and cannot have trips which reach a given distance and remain within the MSA. Those trips likely originated from (or were destined to) locations outside the MSA. Any trips simulated in excess of 60km were excluded. An interval size (s) of 5 km was chosen based on ensuring sufficient sample size in each MSA. A threshold (S) of 60 km included more than 95% of work trips in the tested MSAs.

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Additional Information

D.G. and D.L. wrote this manuscript text and D.L. prepared Figures 1-2 while D.G. prepared Figures 3-4.

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Tables

MSA	1990	2000	2010	t-stat	p-value	C.I.
Atlanta	1.213	1.213	1.217	5.541	3.02×10^{-8}	99%
Austin	1.294	1.289	1.293	2.089	3.67×10^{-2}	95%
Baltimore	1.215	1.217	1.232	4.985	6.21×10^{-7}	99%
Boston	1.192	1.192	1.192	-3.630	2.84×10^{-4}	99%
Buffalo	1.172	1.186	1.179	7.809	5.80×10^{-15}	99%
Charlotte	1.218	1.227	1.220	0.365	7.15×10^{-1}	0%
Chicago	1.189	1.187	1.191	1.653	9.83×10^{-2}	90%
Cincinnati	1.280	1.271	1.272	2.685	7.24×10^{-3}	99%
Cleveland	1.164	1.166	1.166	-3.538	4.03×10^{-4}	99%
Columbus	1.190	1.191	1.190	0.266	7.90×10^{-1}	0%
Dallas-Fort Worth	1.226	1.227	1.236	3.521	4.31×10^{-4}	99%
Denver	1.326	1.320	1.342	3.131	1.74×10^{-3}	99%
Detroit	1.189	1.198	1.192	4.507	6.59×10^{-6}	99%
Grand Rapids	1.233	1.239	1.240	-0.537	5.91×10^{-1}	0%
Hampton Roads	1.338	1.306	1.307	5.001	5.72×10^{-7}	99%
Hartford	1.214	1.227	1.228	3.856	1.15×10^{-4}	99%
Honolulu	1.467	1.452	1.443	3.425	6.15×10^{-4}	99%
Houston	1.262	1.261	1.263	2.396	1.66×10^{-2}	95%
Indianapolis	1.185	1.203	1.198	4.713	2.45×10^{-6}	99%
Inland Empire	1.315	1.335	1.351	5.574	2.50×10^{-8}	99%
Jacksonville	1.309	1.310	1.305	4.710	2.48×10^{-6}	99%
Kansas City	1.252	1.254	1.247	7.475	7.79×10^{-14}	99%
Las Vegas	1.327	1.338	1.316	0.333	7.39×10^{-1}	0%
Los Angeles	1.242	1.230	1.236	5.700	1.20×10^{-8}	99%
Louisville	1.295	1.296	1.307	-6.401	1.55×10^{-10}	99%
Memphis	1.257	1.272	1.254	2.233	2.55×10^{-2}	95%
Milwaukee	1.174	1.178	1.168	1.173	2.41×10^{-1}	0%
Minneapolis-St.Paul	1.230	1.223	1.229	2.090	3.67×10^{-2}	95%
Nashville	1.287	1.326	1.285	0.181	8.56×10^{-1}	0%
New Orleans	1.276	1.301	1.335	3.231	1.23×10^{-3}	99%
New York	1.233	1.219	1.212	1.094	2.74×10^{-1}	0%
Oklahoma City	1.263	1.253	1.247	3.356	7.90×10^{-4}	99%
Orlando	1.306	1.270	1.320	3.853	1.17×10^{-4}	99%
Philadelphia	1.169	1.176	1.171	3.479	5.04×10^{-4}	99%
Phoenix	1.262	1.301	1.278	2.082	3.74×10^{-2}	95%
Pittsburgh	1.255	1.251	1.270	-1.158	2.47×10^{-1}	0%
Portland	1.405	1.418	1.441	2.748	6.00×10^{-3}	99%
Providence	1.226	1.226	1.234	13.346	1.35×10^{-40}	99%
Raleigh	1.199	1.208	1.208	8.596	8.37×10^{-18}	99%
Rochester, NY	1.204	1.194	1.209	1.453	1.46×10^{-1}	0%
Sacramento	1.435	1.456	1.396	-7.771	7.88×10^{-15}	99%
Salt Lake City	1.355	1.436	1.382	3.556	3.77×10^{-4}	99%
San Antonio	1.312	1.298	1.294	-2.237	2.53×10^{-2}	95%
San Diego	1.413	1.386	1.393	4.161	3.17×10^{-5}	99%
San Francisco	1.373	1.356	1.393	7.955	1.82×10^{-15}	99%
San Jose	1.395	1.421	1.403	0.092	9.27×10^{-1}	0%
Seattle	1.408	1.386	1.409	4.248	2.16×10^{-5}	99%
South Florida	1.218	1.231	1.238	6.313	2.76×10^{-10}	99%
St. Louis	1.317	1.312	1.323	1.065	2.87×10^{-1}	0%
Tampa Bay	1.252	1.242	1.269	10.425	1.97×10^{-25}	99%
Washington	1.289	1.264	1.275	-2.514	1.19×10^{-2}	95%
Average	1.271	1.273	1.274			

Table 1: Unweighted Circuities (1990-2010)

MSA	1990	2000	2010	t-stat	p-value	C.I.
Atlanta	1.287	1.304	1.318	8.388	5.02×10^{-17}	99%
Austin	1.371	1.359	1.382	2.401	1.63×10^{-2}	95%
Baltimore	1.296	1.288	1.316	7.273	3.55×10^{-13}	99%
Boston	1.278	1.276	1.263	-5.123	3.01×10^{-7}	99%
Buffalo	1.237	1.256	1.258	12.311	8.38×10^{-35}	99%
Charlotte	1.292	1.300	1.294	0.522	6.01×10^{-1}	0%
Chicago	1.266	1.257	1.275	2.567	1.03×10^{-2}	95%
Cincinnati	1.347	1.352	1.362	3.817	1.35×10^{-4}	99%
Cleveland	1.253	1.239	1.243	-5.398	6.75×10^{-8}	99%
Columbus	1.280	1.280	1.281	0.366	7.14×10^{-1}	0%
Dallas-Fort Worth	1.297	1.298	1.319	4.462	8.14×10^{-6}	99%
Denver	1.361	1.343	1.374	3.360	7.80×10^{-4}	99%
Detroit	1.256	1.263	1.264	6.510	7.53×10^{-11}	99%
Grand Rapids	1.299	1.294	1.297	-0.769	4.42×10^{-1}	0%
Hampton Roads	1.352	1.370	1.368	7.287	3.20×10^{-13}	99%
Hartford	1.282	1.290	1.288	5.484	4.18×10^{-8}	99%
Honolulu	1.420	1.407	1.435	4.176	2.96×10^{-5}	99%
Houston	1.338	1.329	1.347	2.674	7.50×10^{-3}	99%
Indianapolis	1.277	1.292	1.284	6.517	7.21×10^{-11}	99%
Inland Empire	1.323	1.347	1.368	5.957	2.58×10^{-9}	99%
Jacksonville	1.347	1.380	1.362	5.913	3.37×10^{-9}	99%
Kansas City	1.294	1.310	1.319	9.969	2.13×10^{-23}	99%
Las Vegas	1.316	1.329	1.319	0.399	6.90×10^{-1}	0%
Los Angeles	1.274	1.276	1.307	7.893	2.98×10^{-15}	99%
Louisville	1.397	1.370	1.358	-8.518	1.64×10^{-17}	99%
Memphis	1.319	1.340	1.331	3.309	9.37×10^{-4}	99%
Milwaukee	1.235	1.254	1.238	1.822	6.84×10^{-2}	90%
Minneapolis-St.Paul	1.301	1.290	1.310	2.842	4.49×10^{-3}	99%
Nashville	1.365	1.414	1.366	0.220	8.26×10^{-1}	0%
New Orleans	1.365	1.363	1.390	4.531	5.88×10^{-6}	99%
New York	1.293	1.298	1.300	1.339	1.81×10^{-1}	0%
Oklahoma City	1.297	1.315	1.316	4.846	1.26×10^{-6}	99%
Orlando	1.358	1.329	1.380	5.047	4.49×10^{-7}	99%
Philadelphia	1.254	1.271	1.269	4.717	2.39×10^{-6}	99%
Phoenix	1.310	1.338	1.331	2.220	2.64×10^{-2}	95%
Pittsburgh	1.380	1.377	1.374	-1.419	1.56×10^{-1}	0%
Portland	1.454	1.462	1.484	3.015	2.57×10^{-3}	99%
Providence	1.296	1.296	1.322	15.283	1.14×10^{-52}	99%
Raleigh	1.267	1.287	1.296	14.685	9.07×10^{-49}	99%
Rochester, NY	1.277	1.267	1.281	2.202	2.77×10^{-2}	95%
Sacramento	1.449	1.464	1.411	-8.553	1.21×10^{-17}	99%
Salt Lake City	1.341	1.414	1.378	4.773	1.82×10^{-6}	99%
San Antonio	1.410	1.384	1.394	-2.615	8.94×10^{-3}	99%
San Diego	1.411	1.399	1.437	4.614	3.95×10^{-6}	99%
San Francisco	1.385	1.402	1.439	9.200	3.63×10^{-20}	99%
San Jose	1.410	1.430	1.411	0.110	9.12×10^{-1}	0%
Seattle	1.425	1.398	1.465	5.132	2.87×10^{-7}	99%
South Florida	1.289	1.299	1.307	7.321	2.48×10^{-13}	99%
St. Louis	1.380	1.369	1.389	1.334	1.82×10^{-1}	0%
Tampa Bay	1.313	1.317	1.334	12.623	1.68×10^{-36}	99%
Washington	1.371	1.349	1.354	-3.360	7.79×10^{-4}	99%
Average	1.327	1.332	1.339			

Table 2: Weighted Circuities (1990-2010)

Year (Ascending)	Count
1990-2000-2010	14
1990-2010-2000	8
2000-1990-2010	13
2000-2010-1990	3
2010-1990-2000	1
2010-2000-1990	2
Total MSAs with significant changes	41
Total MSAs	51

Table 3: Frequencies of Statistically Significant Circuity Trends.

	1990			2000			2010		
MSA	ζ	β	r^2	ζ	β	r^2	ζ	β	r^2
Atlanta	-0.05823	0.4321	0.997	-0.06512	0.4687	0.996	-0.06962	0.4777	0.991
Austin	-0.06030	0.5047	0.976	-0.04778	0.4577	0.951	-0.06266	0.5037	0.988
Baltimore	-0.05200	0.4102	0.984	-0.05241	0.4167	0.971	-0.05439	0.4344	0.915
Boston	-0.05162	0.3879	0.953	-0.04943	0.3810	0.948	-0.05133	0.3865	0.961
Buffalo	-0.03442	0.2957	0.979	-0.03864	0.3299	0.986	-0.04001	0.3256	0.972
Charlotte	-0.05186	0.4155	0.932	-0.05849	0.4483	0.960	-0.04520	0.3855	0.845
Chicago	-0.05291	0.3912	0.990	-0.05395	0.4043	0.996	-0.05524	0.4022	0.993
Cincinnati	-0.04124	0.4142	0.956	-0.05216	0.4560	0.940	-0.04559	0.4301	0.857
Cleveland	-0.04446	0.3321	0.955	-0.04742	0.3494	0.948	-0.04822	0.3474	0.967
Columbus	-0.05327	0.3899	0.982	-0.05376	0.3965	0.985	-0.05642	0.3966	0.950
Dallas-Fort Worth	-0.06492	0.4660	0.997	-0.05433	0.4296	0.994	-0.06434	0.4720	1.000
Denver	-0.02358	0.3811	0.958	-0.01959	0.3637	0.797	-0.02491	0.3952	0.975
Detroit	-0.04188	0.3472	0.963	-0.04312	0.3645	0.990	-0.04461	0.3578	0.967
Grand Rapids	-0.03937	0.3691	0.942	-0.03673	0.3678	0.970	-0.03019	0.3370	0.887
Hampton Roads	0.00290	0.2848	0.013	-0.04344	0.4506	0.784	-0.01853	0.3548	0.336
Hartford	-0.03171	0.3234	0.897	-0.03513	0.3474	0.936	-0.03771	0.3585	0.914
Honolulu	0.02964	0.2615	0.854	0.02782	0.2576	0.857	0.01495	0.3089	0.869
Houston	-0.05286	0.4491	0.997	-0.04889	0.4408	0.957	-0.06169	0.4805	0.992
Indianapolis	-0.05276	0.3845	0.972	-0.05768	0.4284	0.992	-0.05520	0.4062	0.983
Inland Empire	-0.02887	0.3887	0.989	-0.02046	0.3726	0.820	-0.01427	0.3546	0.892
Jacksonville	-0.02458	0.3748	0.827	-0.04517	0.4617	0.984	-0.04100	0.4283	0.985
Kansas City	-0.03909	0.3819	0.971	-0.04088	0.3921	0.999	-0.04352	0.3943	0.993
Las Vegas	0.00025	0.2842	0.001	0.00018	0.2899	0.025	-0.00528	0.2958	0.886
Los Angeles	-0.02052	0.3028	0.781	-0.03305	0.3471	0.926	-0.03425	0.3580	0.757
Louisville	-0.05151	0.4749	0.926	-0.03973	0.4275	0.931	-0.03255	0.4047	0.779
Memphis	-0.04381	0.4091	0.973	-0.04786	0.4432	0.988	-0.05315	0.4401	0.972
Milwaukee	-0.03570	0.3073	0.941	-0.04266	0.3424	0.954	-0.03521	0.2996	0.908
Minneapolis-St.Paul	-0.04722	0.3995	0.990	-0.05455	0.4281	0.987	-0.05764	0.4396	0.989
Nashville	-0.05033	0.4527	0.993	-0.05928	0.5242	0.996	-0.06460	0.5022	0.997
New Orleans	-0.03600	0.4076	0.767	-0.02686	0.3855	0.688	-0.01331	0.3600	0.204
New York	-0.03698	0.3636	0.981	-0.05176	0.4177	0.988	-0.04010	0.3564	0.942
Oklahoma City	-0.02432	0.3270	0.995	-0.04423	0.4079	0.998	-0.04293	0.3889	0.993
Orlando	-0.03329	0.4033	0.997	-0.03773	0.4017	0.988	-0.04051	0.4366	0.995
Philadelphia	-0.04931	0.3565	0.987	-0.05473	0.3922	0.978	-0.05044	0.3603	0.971
Phoenix	-0.03304	0.3675	0.997	-0.02684	0.3778	0.979	-0.03439	0.3815	0.974
Pittsburgh	-0.05723	0.4594	0.990	-0.06503	0.4929	0.985	-0.06105	0.4782	0.988
Portland	-0.03243	0.4762	0.856	-0.03178	0.4863	0.933	-0.03297	0.4986	0.964
Providence	-0.01163	0.2763	0.108	-0.02372	0.3179	0.476	-0.03402	0.3532	0.784
Raleigh	-0.05614	0.4095	0.984	-0.06599	0.4618	0.984	-0.06242	0.4393	0.962
Rochester, NY	-0.03945	0.3449	0.977	-0.03872	0.3366	0.986	-0.04054	0.3538	0.968
Sacramento	-0.01136	0.4047	0.909	-0.01090	0.4180	0.835	-0.00966	0.3742	0.678
Salt Lake City	0.00151	0.2976	0.052	0.00842	0.3261	0.677	0.00081	0.3234	0.011
San Antonio	-0.06932	0.5458	0.975	-0.06336	0.5216	0.990	-0.06376	0.5068	0.998
San Diego	0.00070	0.3423	0.017	-0.01039	0.3701	0.902	-0.02033	0.4143	0.947
San Francisco	-0.02030	0.4028	0.825	-0.03091	0.4398	0.872	-0.02632	0.4387	0.965
San Jose	-0.01012	0.3727	0.681	-0.00840	0.3810	0.471	-0.01027	0.3681	0.346
Seattle	-0.01773	0.4166	0.864	-0.00796	0.3589	0.860	-0.03205	0.4746	0.896
South Florida	-0.03926	0.3639	0.978	-0.03475	0.3543	0.878	-0.03886	0.3711	0.967
St. Louis	-0.04015	0.4398	0.930	-0.04502	0.4620	0.950	-0.05429	0.4965	0.995
Tampa Bay	-0.04075	0.3962	0.993	-0.04658	0.4173	0.997	-0.03513	0.3808	0.940
Washington	-0.05740	0.4936	0.992	-0.06451	0.5087	0.973	-0.05669	0.4755	0.952
Average	-0.03589	0.3860	0.854	-0.03913	0.4044	0.901	-0.03984	0.4021	0.882
σ_ζ	0.02019	-	-	0.02000	-	-	0.01878	-	-

Table 4: Summary Table of ζ, β, and respective r^2 values

Trips	Matrix	C	σ
2,000	[100x20]	1.198185	0.012191
8,000	[200x40]	1.180127	0.010263
50,000	[500x100]	1.184671	0.006425
200,000	[1000x200]	1.186153	0.009032

Table 5: Sampling iterations (trips) performed on Miami, Florida MSA. This table shows various levels of OD Matrix sizes used prior to testing all 51 MSAs. The results shown are only for the Miami, FL MSA. Miami was chosen because it is a relatively large MSA. As can be seen from the standard deviations tabulated, there is no significant difference between the variation of the matrices that generate 50,000, and 200,000 trip iterations (The σ is actually higher in the 200,000 matrix), which is the reason for performing 50,000 iterations on each metropolitan area on all subsequent tests.

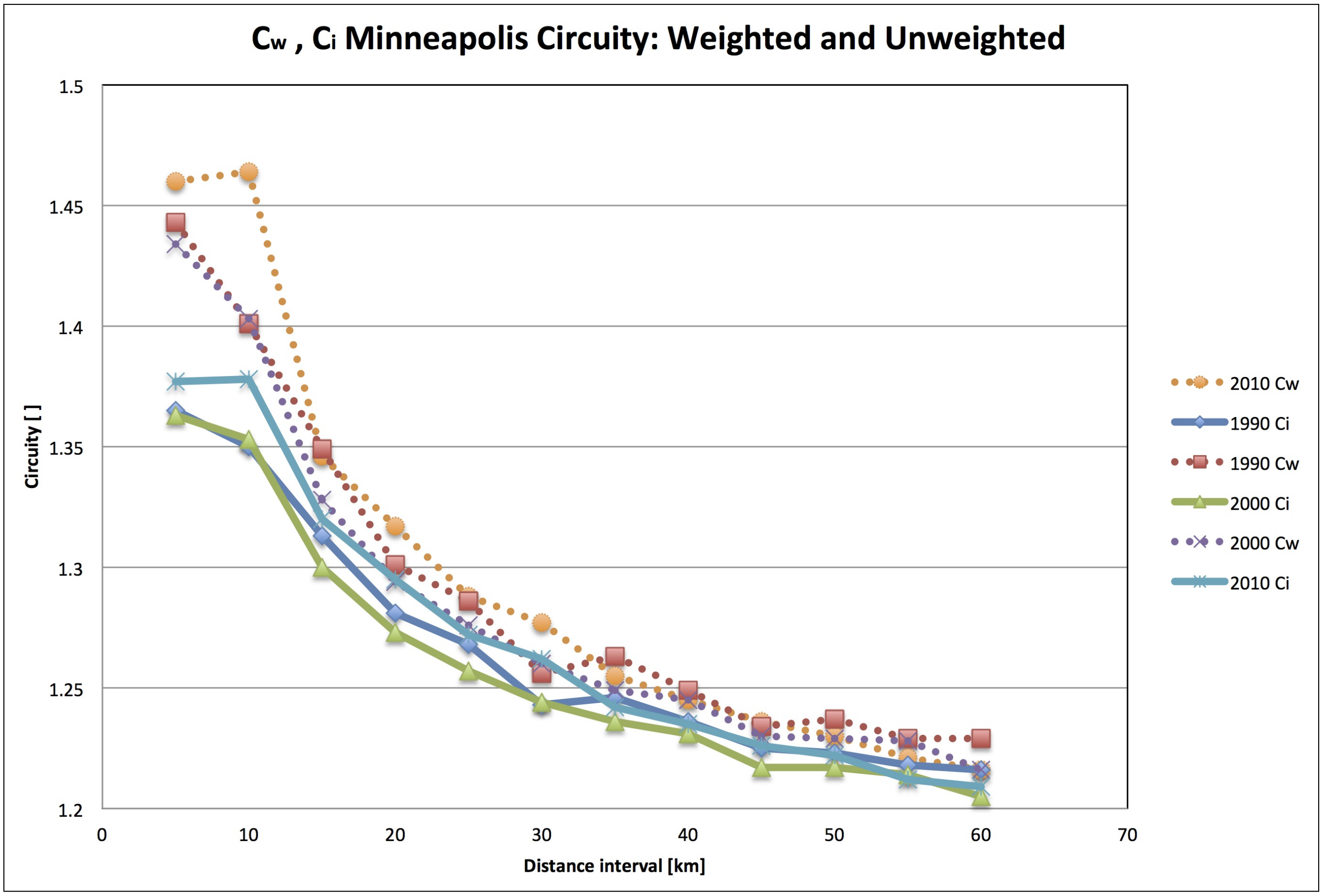

Figure 1: Circuity by distance interval in Minneapolis

Figures

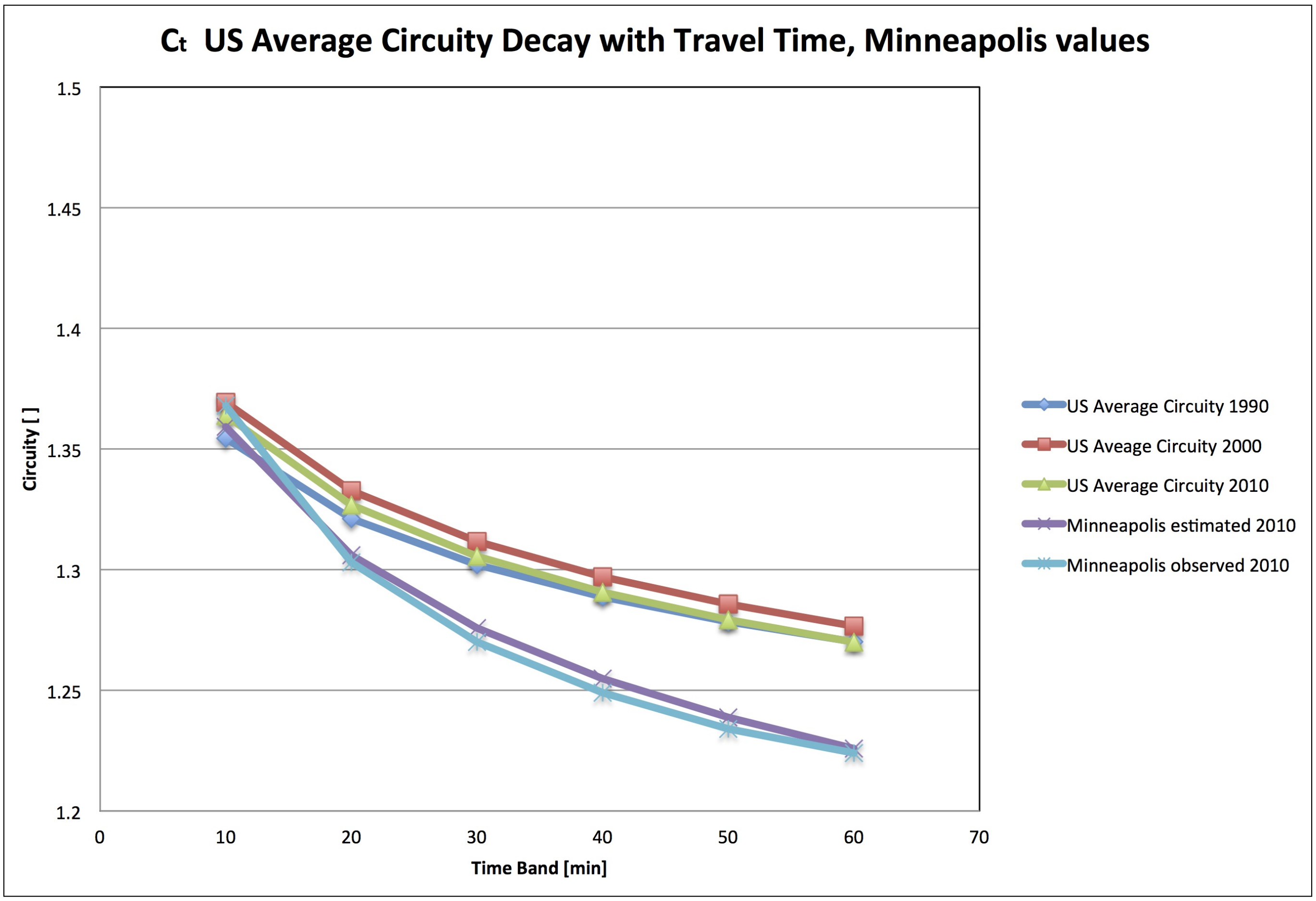

Figure 2: Circuity by time interval, US average and Minneapolis. An average weighted circuity function averaged over all 51 MSAs studied in 1990, 2000, and 2010.

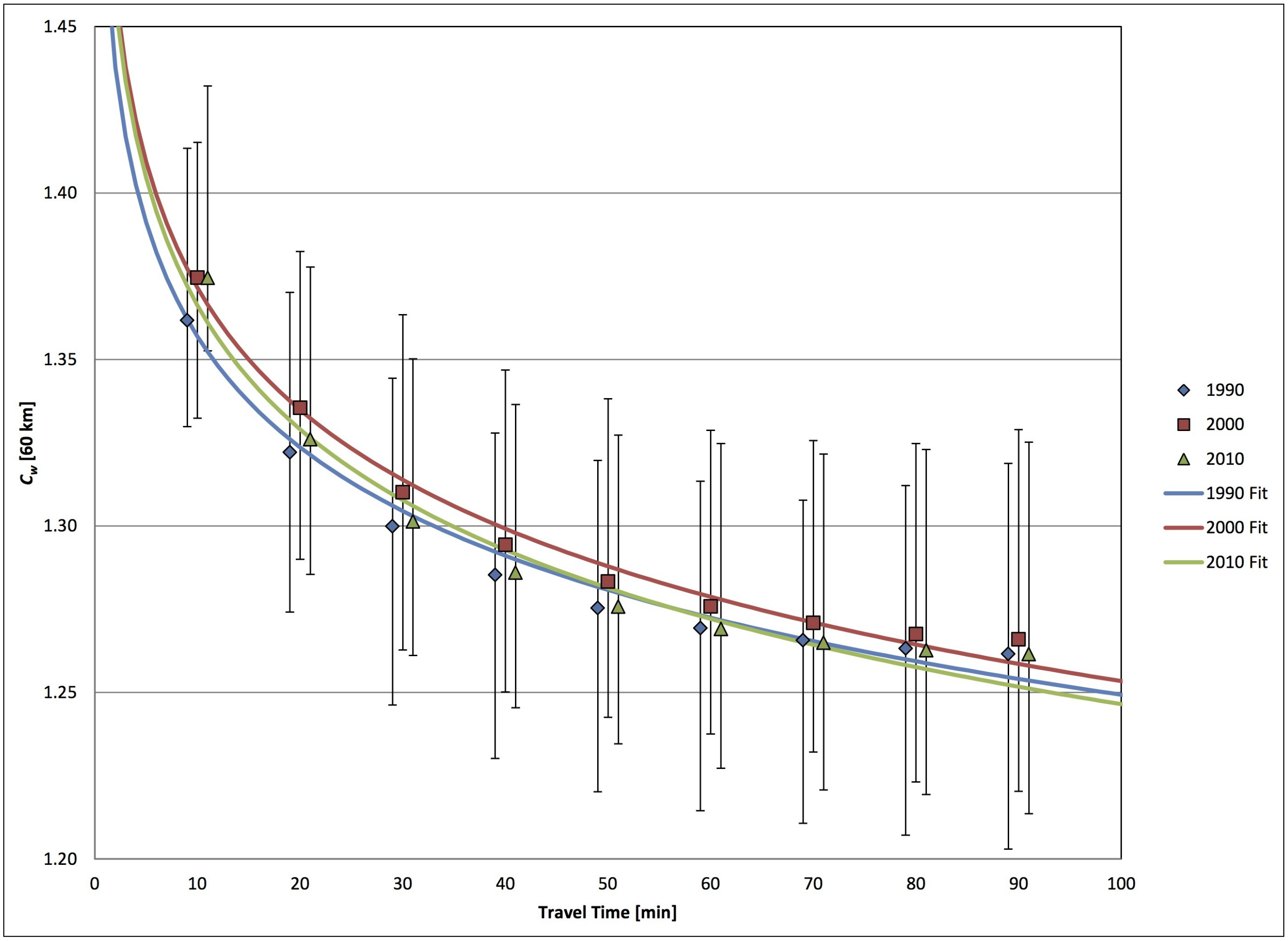

Figure 3: Circuity by travel time, US average. An overlay of actual circuity data with plotted US averages showing the ability of Equation 3 to model circuity.

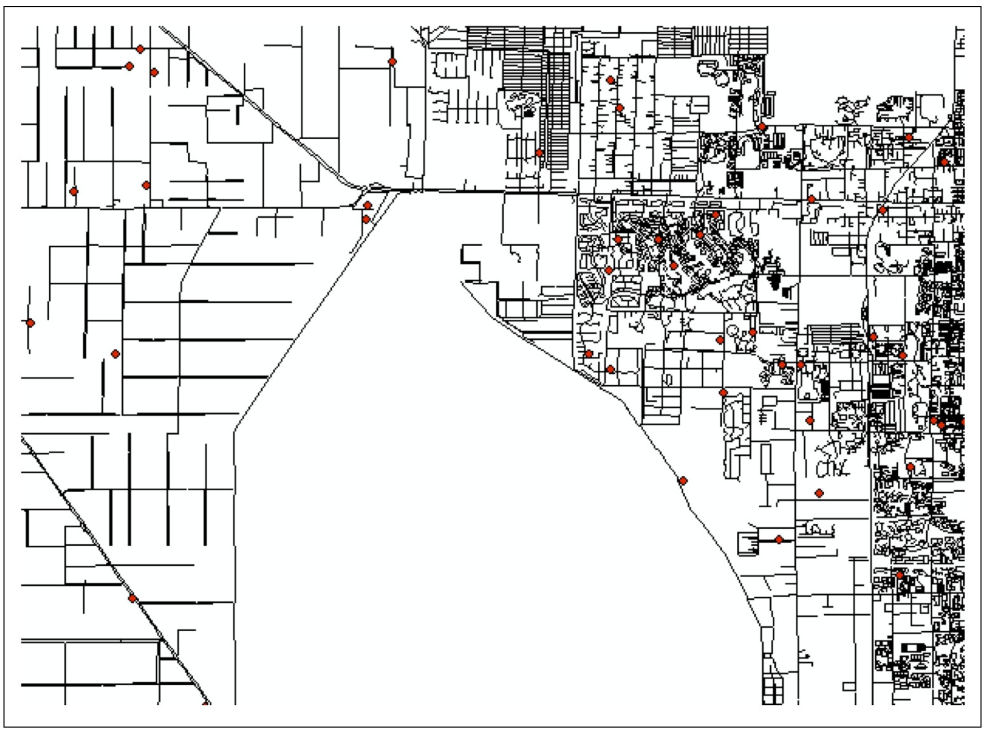

Figure 4: A selected portion of the Miami road network with generated origins overlaid in red.